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Nonlinear heat effects on African maize as evidenced by historical yield trials

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New approaches are needed to accelerate understanding of climate impacts on crop yields, particularly in tropical regions. Past studies have relied mainly on crop-simulation models[1,2] or statistical analyses based on reported harvest data[3,4], each with considerable uncertainties and limited applicability to tropical systems. However, a wealth of historical crop-trial data exists in the tropics that has been previously untapped for climate research. Using a data set of more than 20,000 historical maize trials in Africa, combined with daily weather data, we show a nonlinear relationship between warming and yields. Each degree day spent above 30 °C reduced the final yield by 1% under optimal rain-fed conditions, and by 1.7% under drought conditions. These results are consistent with studies of temperate maize germplasm in other regions, and indicate the key role of moisture in maize's ability to cope with heat. Roughly 65% of present maize-growing areas in Africa would experience yield losses for 1 °C of warming under optimal rain-fed management, with 100% of areas harmed by warming under drought conditions. The results indicate that data generated by international networks of crop experimenters represent a potential boon to research aimed at quantifying climate impacts and prioritizing adaptation responses, especially in regions such as Africa that are typically thought to be data-poor.

Effective adaptation of agriculture to climate change in the developing world will require at least two pieces of information: the relative risks posed by climate change across different locations and cropping systems, which is useful for prioritizing the use of scarce resources devoted to adaptation, and the likely mechanisms of potential damage from climate change, to prioritize among different types of possible solution. For example, a main strategy will probably be breeding for improved abiotic stress, but the particular traits that present the largest opportunities for progress are often unclear[5,6].

Present approaches to addressing both of these needs are limited, especially in developing countries. For example, simulation models have been calibrated mainly in temperate systems, do not include all potentially relevant processes, and are dependent on inputs that prescribe cultivar characteristics, management practices, soil properties and initial conditions, all of which are imperfectly known[7,8]. Statistical approaches are frequently limited by the quantity and quality of data used to train them, which results in fairly large uncertainties[4], although the data sets available for statistical approaches are improving[9,10].

Here we introduce an empirical approach that relies on newly available data from a network of cropping trials. In this case, we focus on field trials for tropical maize conducted in Africa in 1999–2007 on a network of 123 research stations managed by the International Maize and Wheat Improvement Center (CIMMYT), National Agricultural Research Programs and private seed companies[11] (Fig. 1). The original purpose of these trials was to test new varieties across a range of environmental conditions, to identify robust lines for release to farmers. Most trials were carried out under 'optimal' management, that is, rain-fed conditions using site-specific agronomic treatments to minimize nutrient, water, disease and other stresses. The second most common treatment was managed drought stress, where the varieties were irrigated in a rain-free period until plants were established, and then irrigation was cut off to induce moisture stress during flowering and grain-filling[11]. The varieties included in this data set are grown or intended for farmers' fields throughout Africa, nearly all of which are rain-fed. We refer to each combination of maize variety, station, year and management regime as a single trial.

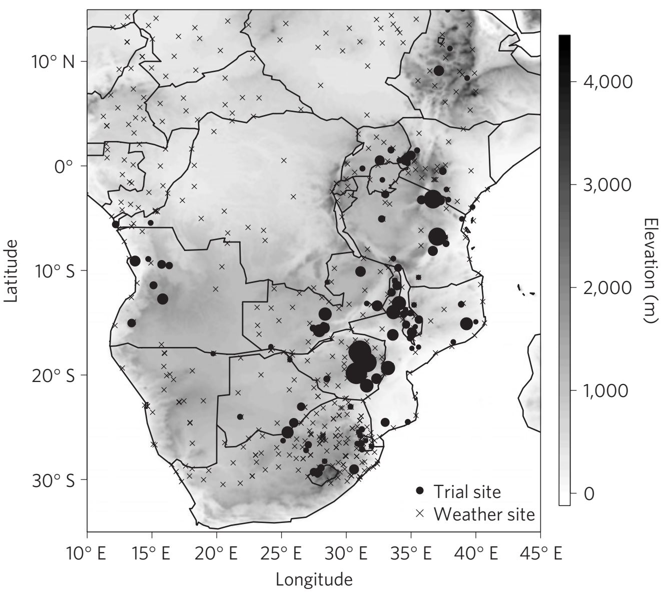

Figure 1 | The study region in Africa. The circles show locations of crop trials, with the size of the circle indicating the number of trials per site (ranging from 20 to 1,249). Weather stations with daily data for at least some portion of the study period 1999–2007 are marked as crosses. The background map shows elevation, with higher altitudes appearing darker.

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For each trial, we recreated the daily temperature and precipitation using thin-plate spline interpolation of daily records from nearby weather stations (see Methods). Various summary statistics of the growing season weather were then computed, including growing degree sums, averages for critical development phases and time spent above critical temperature thresholds. In total, 17,713 trials with optimal management and 3,244 with managed drought stress for the period 1999–2007 were used. The effect of weather on yields was modelled using a linear fixed-effects model, with three weather variables:

$$Y_{i,s,t} = \mathbf{a}X_{i,s,t} + \mathbf{b}_s + \mathbf{c}_t + \varepsilon \quad (1)$$

where $Y_{i,s,t}$ is the natural logarithm of reported yield (log(yield)) for the ith trial at station s in year t, $X_{i,s,t}$ is a vector of climate variables for that trial, $\mathbf{a}$ is a vector of coefficients, $\mathbf{b}_s$ represents an intercept associated with station s, $\mathbf{c}_t$ represents an intercept for year t and ε is an error term. The weather variables in $X_{i,s,t}$ in our initial model included three terms: $GDD_{8,30}$, the sum of growing degree days between 8 °C and 30 °C for the growing season (defined as the interval from sowing to 150 days after sowing for each trial), GDD_{30+}, the sum of growing degree days above 30 °C, and $prec_{anth}$, total precipitation for the 21-day period centred on anthesis. $GDD_{8,30}$ represents a typical measure used to predict maize development rates[12], and is closely related to average growing-season temperature (T_{avg}), with a correlation over 0.98 in our sample. GDD_{30+} is a measure of exposure to temperatures above a threshold at which warming can be quite harmful to growth and reproductive processes[13], and is only weakly correlated with T_{avg} ($r = 0.49$) and $GDD_{8,30}$ ($r = 0.45$; Supplementary Fig. S1). Precipitation around anthesis is used because maize plants are particularly susceptible to drought stress at this stage[6,14–17]. Alternative formulations were tested, with similar results as described in the Supplementary Information. Inclusion of the coefficients $\mathbf{b}_s$ and $\mathbf{c}_t$ in equation (1) helps to ensure that any perceived effect of weather is not due to differences between sites or years that may arise from omitted variables. Within sites, omitted variables such as use of fertilizers, herbicides or labour are likely to be uniform, and any variations are assumed orthogonal to weather because the locations of trials were randomized within the experiment station.

We find a highly significant ($P < 0.01$) effect of temperature on maize yields, with clear differences between optimal and drought conditions (Fig. 2a). Both management systems show fairly modest and statistically insignificant ($P > 0.05$) sensitivities to increased degree days between 8 °C and 30 °C. In contrast GDD_{30+} exhibits a marked negative effect on yields, with the effect larger under drought conditions. As the units of yields are in log, a coefficient of −0.01 (or −0.017) indicates that each additional degree day above 30 °C reduces the final yield by 1% (or 1.7%) under optimal (or drought) conditions.

The importance of GDD_{30+} is consistent with the only previous study to our knowledge with a comparable sample size, which focused on temperate maize in the US (ref. 13). As in the optimal management case here, they found that increases in $GDD_{8,30}$ improved yields but each additional GDD_{30+} reduced yields by about 1%. In our drought management case, yields are reduced by roughly 1.7% for each additional GDD_{30+}. This demonstrates the importance of moisture status in the response to heat, an insight that is not possible from evaluating data from a single or, as in ref. 13, unknown mixture of management regimes. The interaction between moisture and heat could indicate that the main mechanism of heat damage is by reducing soil moisture and increasing the severity of drought, that the ability of maize to cope with direct effects of heat on cellular processes is dependent on plant water availability status, or both. For example, evaporative cooling is an important mechanism for coping with heat, but can occur only with ample soil moisture[18].

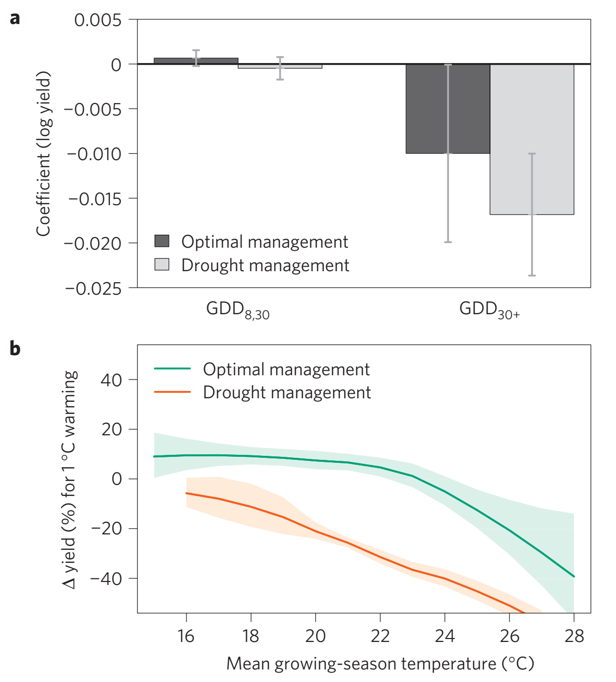

Figure 2 | The effect of heat on maize yields. a, Regression estimates of the effects of an increase of $GDD_{8,30}$ and GDD_{30+} by 1 degree day, using data from trials managed for optimal ($n = 17{,}713$) or drought ($n = 3{,}244$) conditions. Error bars indicate 95% confidence interval using robust standard errors clustered by site–year. **b**, Model estimate of yield impact of 1 °C warming for trials at different average growing-season temperatures, using regression equations for trials with optimal or drought management. The lines are the best fits to the mean impact at each temperature level, and the shaded areas show an estimate of the 95% confidence interval using robust standard errors.

The negative impact of GDD_{30+} found here and elsewhere indicates that daytime warming is more harmful to maize than night-time warming. To corroborate this, we carried out a regression with linear and quadratic terms for growing-season average daily maximum and minimum temperature. The results confirmed that warming is more harmful during the day, and under optimal management warming at night can even be beneficial (Supplementary Fig. S2). This result is probably crop dependent; for instance, recent analysis of rice indicates that night-time warming is more harmful than daytime warming[10].

One mechanism of yield loss from daytime heat and moisture stress is damage to reproductive organs. To evaluate this further, a regression with $GDD_{8,30}$ and GDD_{30+} split across three stages of the growing season was carried out. The results supported an important role for processes related to flowering, as sensitivity to GDD_{30+} was highest under optimal management for the 21 days around silking, and under drought management for pre-silking and silking stages (Supplementary Fig. S3).

The net effect of warming on yields was computed for each trial by artificially raising observed temperatures on each day by 1 °C, recomputing temperature indices such as $GDD_{8,30}$, and using the regression equations to predict the new yield. Results were summarized as averages for all trials at a given baseline temperature to assess the nonlinearity of warming effects (Fig. 2b). For optimal management, at present, maize growing below ∼23 °C in average growing-season temperature tends to gain from warming, owing to positive effects of $GDD_{8,30}$, whereas yields of maize grown in areas above this baseline temperature tend to decline with

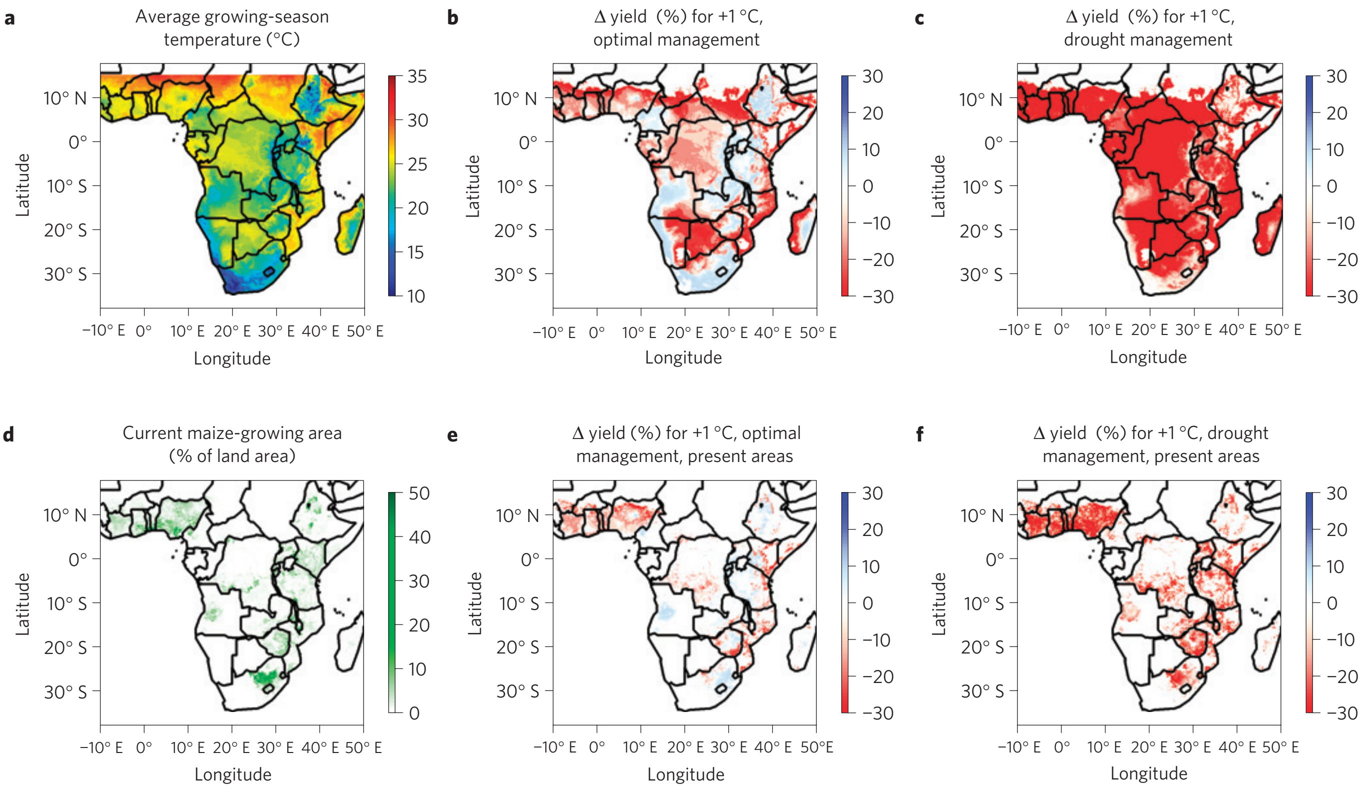

Figure 3 | Model estimates of maize yield changes for 1 °C warming. a–c, Present growing-season average temperature (**a**) and estimated impacts of 1 °C warming for all areas for optimal (**b**) and drought (**c**) management. **d–f**, Present maize-growing area (fraction of grid cell; ref. 23; **d**) and estimated impacts of 1 °C warming for areas with at least 1% of maize (**e**,**f**).

warming. Sites above 25 °C in average temperature decline quite rapidly, albeit with considerable uncertainty, because of frequent exposure to temperatures above 30 °C, with more than 10% yield loss per °C of warming.

Under drought conditions, even the coolest trials are harmed by 1 °C warming, with losses exceeding 40% at the hottest sites. Again, this emphasizes the importance of moisture in the ability of maize to cope with heat. Similarly, studies for maize in the US have shown much greater sensitivity to hot days for eastern, rain-fed states than in the western states, where irrigation is much more common[13].

The relationships derived from trial data were used to map potential impacts for maize under optimal or drought management across sub-Saharan Africa (Fig. 3). Under optimal management, negative yield impacts were projected for roughly 65% of the area where maize is harvested at present in Africa. All maize areas were projected to exhibit yield declines under drought management, with more than 75% of areas predicted to decline by at least 20% for 1 °C warming.

It is difficult to relate the management conditions in these trials to those in actual farmers' fields. One clear difference is that these particular trials use fairly high rates of fertilizer to avoid nitrogen (N) stress, whereas most farmers outside South Africa and Zimbabwe have historically applied little N fertilizer. Nitrogen stress tends to mute the response to other stresses, such as moisture or heat[4,19]; thus, the maps in Fig. 3 would exaggerate the impacts on actual farmers under present conditions. However, there are widespread efforts to increase fertilizer rates in Africa to raise average yields[20], and this would tend to bring fields closer to the types of heat sensitivity estimated here. For example, previously estimated responses to warming using country-level data in southern Africa[4], where fertilizer rates are higher, lie between the estimates for optimal and drought conditions estimated here (Supplementary Fig. S4).

Not all maize varieties will respond similarly to climate change, and indeed shifting varieties represents a key potential means of adaptation. The large data set used here affords the opportunity to examine varietal differences (Supplementary Fig. S5), indicating a potentially important role for variety switching as an adaptive response to climate change, although the appropriate switch depends on moisture conditions.

Overall, our results indicate two important conclusions. First, maize yields in Africa may gain from warming at relatively cool sites, but are significantly hurt in areas where temperatures commonly exceed 30 °C. This roughly corresponds to areas with growing season T_{avg} of 23 °C or T_{max} of 28 °C. These conclusions are in line with previous results from process-based models[7,21] or statistical models in Africa that relied on United Nations Food and Agriculture Organization data[4], which showed heterogeneous impacts of climate change that, on average, are quite negative. However, the present study offers more precision than previous studies because of the large sample sizes.

Second, sensitivity to heat is clearly exacerbated in drought conditions, with even the coolest sites hurt by warming in the absence of adequate soil moisture. These results indicate that agronomic measures to improve soil moisture and breeding efforts to produce drought-tolerant crops are not only beneficial for managing present and future risks of drought, but are also probably important strategies to deal with future warming. Conversely, improvements in heat tolerance may limit losses during droughts. Although these conclusions cannot be directly extrapolated to other regions or crops, we believe the approach introduced here has wide applicability in other settings, and for a range of questions that extend beyond the present focus on temperature. For example, international public research organizations, national breeding programmes, and multinational companies possess similar data for many crops and regions.

Methods

Daily minimum and maximum temperatures and precipitation for each trial were estimated by interpolation of daily measurements made in the World Meteorological Organization, World Weather Watch Program (obtained from ftp://ftp.ncdc.noaa.gov/pub/data/gsod). The locations of stations with data are shown in Fig. 1, although many stations have incomplete records over the study period (1999–2007). For each day, a thin-plate spline using latitude (in degrees), longitude (in degrees) and elevation (in kilometres) as predictors was fitted to the available data. Root mean square errors of the model at the World Meteorological Organization sites averaged 1.3 °C for mean temperature and 2.7 mm day^{-1} for precipitation, with cross-validated errors of 1.9 °C and 4.8 mm day^{-1}, respectively.

Growing degree days were estimated from daily T_{min} and T_{max} at each site as:

$$\mathrm{GDD}_{\mathrm{base,opt}} = \sum_{t=1}^{N} \mathrm{DD}_t, \quad \mathrm{DD} = \left\{ \begin{array}{ll} 0 & \text{if } T_t < T_{\mathrm{base}} \\ T - T_{\mathrm{base}} & \text{if } T_{\mathrm{base}} \le T_t \le T_{\mathrm{opt}} \\ T_{\mathrm{opt}} - T_{\mathrm{base}} & \text{if } T_t > T_{\mathrm{opt}} \end{array} \right\} \qquad (2)$$

where t is an individual time step (hour) within the growing season, T_t is the average temperature during this time step (determined by interpolating between T_{min} and T_{max} with a sin curve) and N is the number of hours between sowing and maturity. Only a small subset of sites reported maturity date, and therefore we could not use trial-specific growing season lengths without omitting a large fraction of the data. The average length to maturity for reporting sites (150 days or 3,600 h) was therefore used for all sites. $GDD_{8,30}$ corresponds to equation (2) with $T_{base} = 8$ °C, and $T_{opt} = 30$ °C, which is based on established values for maize[12], whereas GDD_{30+} corresponds to equation (2) with $T_{base} = 30$ °C, and $T_{opt} = \infty$. Daily errors in T estimates will largely cancel when aggregating to growing-season sums, but any residual error will tend to attenuate the regression coefficients toward zero.

Several proxies for soil moisture availability were tested, including precipitation for the 21 days around anthesis (a period commonly viewed as critical to maize[17]), precipitation before anthesis, the difference between precipitation and total potential evapotranspiration before anthesis, and precipitation for the entire growing season. All gave similar results for temperature sensitivity, as did a model without any precipitation term, as well as a model with the measured anthesis–silking interval for the trial, which is a good indicator of moisture stress and a strong predictor of final yield[15,19] (see Supplementary Fig. S6).

In the linear mixed model in equation (1), the coefficients $\mathbf{b}_s$ and $\mathbf{c}_t$ can be treated as either fixed effects, where each site and year has its own independent intercept, or random effects, where the effects are viewed as derived from a Gaussian distribution (that is, $\mathbf{b}_s \sim N(0, \sigma_b{}^2)$). We use the more conservative fixed-effects approach, but results were nearly identical when using random effects. Results were also similar when using actual yields instead of log-transformed yields. Log yields were used to account for the skewed distribution of yields (Supplementary Fig. S1), as commonly done and supported in this case by a theta parameter of 0.5 for the Box–Cox power transformation.

A potential problem when using standard regression is that, if model errors are not independent, the inferred confidence intervals can be overly optimistic. In this context, it is likely that trials conducted for a particular year in a particular station were all affected by the same omitted variables, and therefore errors will not be independent. To account for this, we clustered standard errors by site–year, and use these more conservative estimates of standard errors throughout.

Finally, we note that none of the regression models or impacts shown in Fig. 3 considers fertilization effects of elevated carbon dioxide levels. These effects are expected to be small for C_4 crops such as maize, for which photosynthesis rates do not respond to higher ambient carbon dioxide[22], but may be important under drought conditions when all crops show improved water-use efficiency with elevated carbon dioxide.

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Author contributions

D.B.L. and M.B. conceived the study, M.B., C.M. and B.V. designed and implemented crop trials, D.B.L. analysed data and drafted the paper, and M.B., C.M. and B.V. helped to interpret results and contributed to the writing.

Additional information

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